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Hybrid-Formation of (100), (110), and (111) Ge-on-Insulator Structures on (100) Si Platform

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1. Introduction

Integration of high-mobility channel-materials into Si platform is strongly desired to achieve the next-generation complementary metal-oxide-semiconductor (CMOS) transistors. Recently, we developed "SiGe-mixing triggered rapid melting growth", which enabled the formation of single-crystalline Ge-on-insulator (GOI) structures on Si substrate [1]. Even on quartz substrate, single-crystalline Ge films were obtained by using polycrystalline Si (poly-Si) islands as the growth seeds [2]. However, due to the scattered orientations of the poly-Si seeds, the crystal orientations of the grown GOIs were distributed into (100), (111), and (110) directions. To achieve Ge-channel CMOS transistors with high-speed operation, (111) and (110) Si-seeds should be developed, because the electrons and holes show their highest mobility in (111) and (110) orientation, respectively [3].

In line with this, the present paper mainly describes, (1) advanced metal-induced crystallization, which enables the artificial (111) and (110) Si micro-seeds, and (2) Si-substrate-free rapid-melting growth combined with Si micro-seeds, are reported. This achieves hybrid-formation of (100), (110), and (111) GOI on (100) Si platform.

2. Artificial Si seeds by metal-induced crystallizations

The Al-induced crystallization (AIC) of Si, which is based on the layer-exchange process, is schematically shown in Fig. 1(a). Significant efforts by many researchers have enabled the formation of preferentially (100) or (111) oriented-Si grains. However, the fraction of each orientation is limited to ~60%, furthermore, the orientation itself is not consistent among these reports. Recently, we found that such discrepancy was originated from the different thickness of interfacial Al-oxide layers [4]. To achieve (111) Si-grain by AIC growth, we systematically examine the influence of interfacial Al-oxide layers on AIC growth.

The AIC processes used in the present study are as follows. First, 100 nm-thick Al layers were deposited on quartz by sputtering. XRD measurement revealed the Al layers were preferentially oriented to (111). Then, the Al-oxide layer (amorphous Al_2O_3) was formed by oxidation in ambient, where air-exposure time was chosen in a wide range (t_{air}=5 min-24 h). Subsequently, 100 nm-thick *a*-Si films were deposited by molecular beam deposition, and finally, they were annealed at 450°C for 20-100 h.

Statistical distributions of the crystal orientation of Si grains obtained by AIC growth (t_{air}=5 min, 1 h, and 24 h) are summarized in Fig. 1(b). For the sample with t_{air}=5 min, (100) orientation is preferentially observed. With increasing t_{air}, the fraction of (111) orientation begins to increase. Finally, a very high fraction (~90%) of the (111) orientation is obtained for t_{air}=24 h. The EBSD image shown in Fig. 1(b) clearly demonstrates such nice crystallization. In addition, the full width at half maximum of the statistical distributions of (111) orientation is very narrow (~3.6°). This indicates the high crystallinity of (111) Si grains obtained by AIC growth. Since thicker Al-oxides (t_{air}=24 h) results in slow Si-diffusion for layer-exchange, long-time annealing is required for AIC. Consequently, *a*-Al_2O_3 is crystallized into γ-Al_2O_3(111) on Al(111), which acts as the epitaxial template for (111) Si growth.

Secondary, we examined Ni-mediate induced lateral crystallization (Ni-MILC) to form the (110)-oriented Si seed [Fig. 2 (a)]. The preferential lateral-growth-direction is known to be <111> [5]. Therefore, formation of the Si grains with (110) orientation is expected, because (110) is the lowest-index-plane perpendicular to the <111> direction. In the experiment, 100 nm-thick *a*-Si layers were deposited on quartz, and patterned by wet etching to form island areas (length: 300 μm, width: 20 μm). At the end of the island areas, 5 nm-thick Ni-regions were formed by using electron-beam evaporation and lift-off process. They were annealed at 600°C for 4 h to induced Ni-MILC.

The growth initiated from Ni-region propagates laterally as shown in Fig. 2(b). Statistical distributions of the crystal orientation of Si grains are evaluated using inverse pole figure (IPF), which are displayed in the inset of Fig. 2(c). The fraction of the (110) orientation is summarized as a function of the distance from the Ni-region (*d*) as shown in Fig. 2(c). For near the Ni-region (d<5 μm), the fraction of (110) orientation is limited to ~50%. However, (110) fraction significantly increases with increasing *d*. This suggests that the crystal growth propagates laterally by rotating its crystal orientation into (110) in order to minimize the interface energy [2]. As a result, a very high fraction (~95%) of (110) orientation is obtained for d>10 μm. In this way, (110) Si grain is achieved by Ni-MILC method.

3. Hybrid-formation of (100), (110), and (111) GOI structures on (100) Si platform

Finally, we examined the hybrid-growth of (100), (110), and (111) Ge crystals on insulator. Here, (111) and (110) Si islands obtained by metal-induced crystallizations and (100) Si substrate were used as the seeds for the Ge rapid-melting growth. The structures are schematically shown in Fig. 3(a). After the formation of Si-seeds, 100 nm-thick *a*-Ge layers were deposited and patterned into some narrow stripes (length: ~50 μm, width: 3 μm). Then, they were heat-treated by rapid thermal annealing (RTA) at 1000°C for 1 s to induce the "SiGe-mixing triggered rapid-melting growth" from the Si-seeds.

The EBSD image of the sample after RTA is shown in Fig. 3(b). This clearly demonstrates that the epitaxial growth of these GOI structures were initiated from the Si-seeds and propagated up to ~50 μm keeping their orientation same as the seeds. The cross-sectional TEM images shown in Fig. 3(c) reveal no-defects in the laterally grown

Ge regions. In this way, the hybrid-formation of (100), (110), and (111) GOI structures have been successfully realized on (100) Si platform.

4. Summary

We have developed the Si-substrate free rapid-melting-growth combined with artificial Si seed, where metal-induced crystallizations process enables the formation of (111) and (110) Si-seed. Hybrid-structures, i.e., (100), (111), and (110) GOI on Si platform, demonstrated in our work will be a powerful tool to achieve next-generation CMOS transistors with the operation of high-speed and low-power consumption.

Acknowledgements

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References

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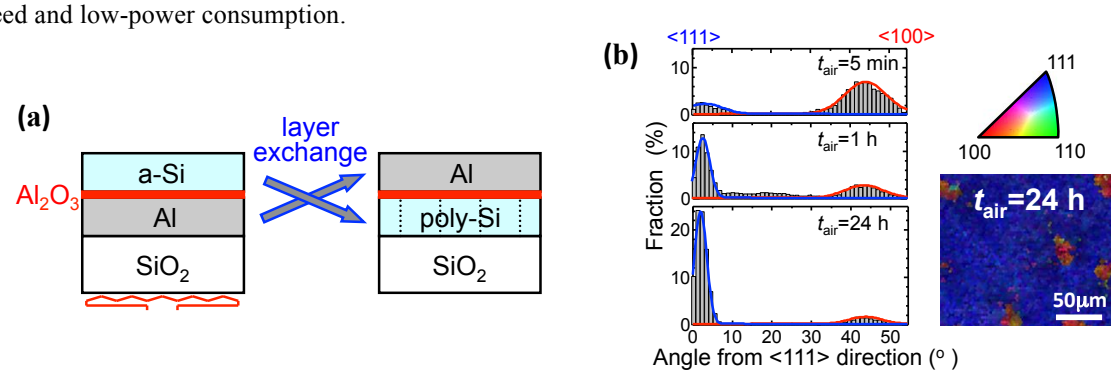

Fig.1. Schematic illustration of AIC process (a). Histgrams of the orientation distributions of AIC-Si obtained from various t_{air} (5 min, 1 h, and 24 h) (b). EBSD image of AIC-Si layer with t_{air}=24 h is also shown in (b).

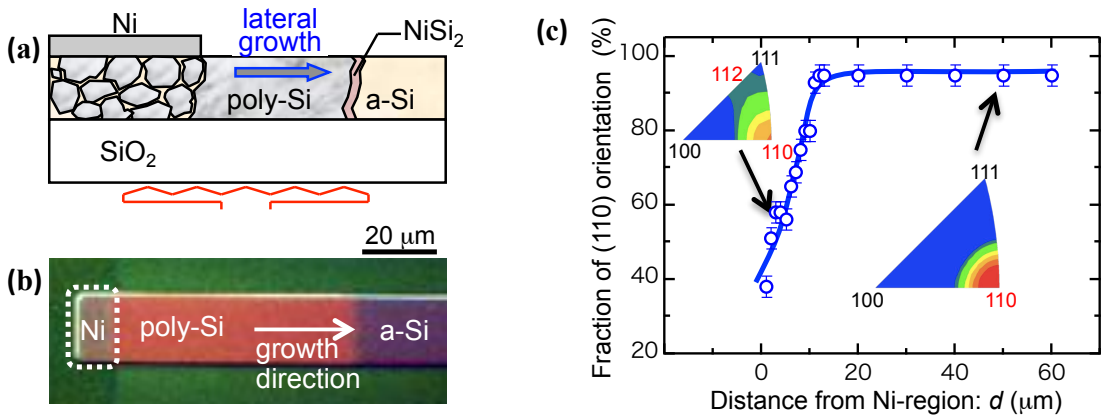

Fig.2. Schematic illustration of MILC process (a), Nomarski optical micrograph after annealing at 600°C for 4 h (b), and the fraction of (110) orientation as a function of distance from the Ni-region (c). Inverse pole figures (IPF) of near (d=3 μm) and away from the Ni-region (d=50 μm) are also shown in (c).

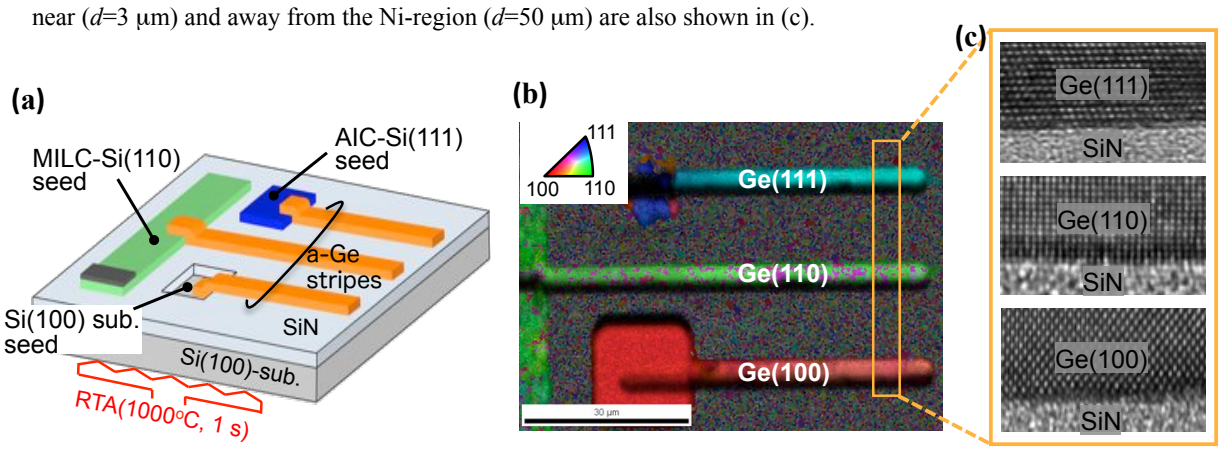

Fig.3. Schematic sample structure for hybrid-formation of (100), (111), and (110) Ge films (a). EBSD image (b) and cross-sectional TEM images (c) of the sample after the SiGe-mixing triggered rapid-melting growth.